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Production of milk foams by steam injection: The effects of steam pressure and nozzle design

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ABSTRACT

Foam properties depend on the physico-chemical characteristics of the continuous phase, the method of production and process conditions employed; however the preparation of barista-style milk foams in coffee shops by injection of steam uses milk as its main ingredient which limits the control of foam properties by changing the biochemical characteristics of the continuous phase. Therefore, the control of process conditions and nozzle design are the only ways available to produce foams with diverse properties. Milk foams were produced employing different steam pressures (100–280 kPa gauge) and nozzle designs (ejector, plunging-jet and confined-jet nozzles). The foamability of milk, and the stability, bubble size and texture of the foams were investigated. Variations in steam pressure and nozzle design changed the hydrodynamic conditions during foam production, resulting in foams having a range of properties. Steam pressure influenced foam characteristics, although the net effect depended on the nozzle design used. These results suggest that, in addition to the physicochemical determinants of milk, the foam properties can also be controlled by changing the steam pressure and nozzle design.

1. Introduction

Foams are gas–liquid systems, which have applications in different fields: cosmetics, drugs, oil extraction, chemical industry and food (Herzhaft, 1999). The incorporation of bubbles into foods helps to improve the texture, appearance and taste whilst decreasing the caloric content (Campbell and Mougeot, 1999). There are several methods employed to incorporate bubbles within food structures: mechanical whipping, air injection, chemical decomposition, fermentation and so on (Campbell and Mougeot, 1999). A less understood method to generate foams is steam injection, may be because of its exclusive applicability to froth the milk used in the preparation of coffee based hot beverage such as cappuccino, latte and mochaccino (Huppertz, 2010).

Steam injection frothing is a non-isothermal method, which employs steam flow to draw air and simultaneously heat up the milk (Silva et al., 2008). Like any foam, the milk foams produced by steam injection begin to destabilize soon after the steam flow is switched off, causing their characteristics to change continuously with time. This process is also accompanied by a drop in temperature which further influences foam properties (Silva et al., 2008).

Foam properties depend on the physico-chemical characteristics of the continuous phase, the method of production and process conditions (Borcherding et al., 2008; Malysa, 1992). A great volume of the available information on foaming of food is focused on studying the effect of the surface active agents (surfactants and proteins) on foams properties (Carrera-Sanchez and Rodrıguez-Patino, 2005; Dickinson, 1999; Marinova et al., 2009; Rodríguez Patino et al., 2008; Wilde et al., 2004). Moreover the published studies on the link between processing conditions and foam properties are restricted to mechanical agitation based methods employed for the production of foams (Balerin et al., 2007; Bals and Kulozik, 2003; Indrawati et al., 2008; Thakur et al., 2003).

Many designs of coffee machines are commercially available to prepare milk foams, which employ a variety of steam injector designs (Borgmann, 1990; Giuliano, 1996; Hsu, 2004; Mahlich and Borgmann, 1989; Stieger and Yoakim, 2006; Stubaus, 1994). Inevitably, each design produces foam by a different mechanism. The oldest method to produce foam by steam injection is to use a nozzle that is placed just below the milk surface. The flow of steam through the nozzle induces air entry. The operator (or

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barista) moves the milk container vertically and horizontally at an appropriate frequency to introduce the air and produce the foam (Giuliano, 1993).

Other sparger designs take advantage of a steam ejector principle to restrict the passage of steam and generate the necessary pressure drop to suck air, or a mix of air and milk, to generate the foam. The simplest ejector based system consists of a nozzle where the steam is allowed to expand, thereby generating a very low pressure and drawing the air through a tube that is connected at the nozzle. The two fluid phases enter a mixing chamber before being introduced into the milk for generating the foam (Borgmann, 1990).

Despite the availability of a large number of patented devices and machines to produce milk foams by steam injection, there are relatively few studies focusing on the effect of process conditions on the properties of foams generated (Deeth and Smith, 1983; Goh et al., 2009; Huppertz, 2010; Kamath et al., 2008; Levy, 2003; Silva et al., 2008). Moreover, the preparation of barista-style milk foams in coffee shops use homogenized pasteurized semi-skimmed milk, which does not permit the control of foam properties formed by merely controlling the biochemical characteristics of the milk. The only way to produce foams with diverse properties, with a given type of milk, is to employ different machine and steam sparger designs. The aim of this study is to evaluate the relationship between the main process parameters (steam pressure and nozzle design) and the principal properties of foams formed.

2. Materials

2.1. Milk supply

Homogenized pasteurized semi-skimmed milk (brand Freshways) was bought from a local shop; this was stored in a fridge (5 ± 1 °C) and processed within 3 days of the purchase. Each batch of milk was characterized by measuring fat, protein, lactose and SNF (solid not fat) contents using a DairyLab (FOSS, Warrington, UK) and the pH was measured using a normal potentiometer.

Commercial red food colouring (Supercook, Leeds, England) was added to the milk in the proportion 10 drops/L, in order to enhance the visualization of the liquid/foam interface in experiments observing the foam generation and stability. The addition of dye at this concentration does not have effect on milk surface tension or foaming properties (Silva et al., 2008).

2.2. Foam generation equipment

A steam injection device constructed previously (Silva et al., 2008) which allowed the formation of foams under controlled and reproducible conditions was used for the experimental study. A control valve connected to a supply of steam regulated the pressures between 0 and 280 kPa gauge, and steam was injected at the following specific pressures (100, 180 and 280 kPa) whilst employing three different sparging units described in the following paragraphs.

2.2.1. Confined-jet

This sparger (Fig. 1A) is based on a commercial design (Francis X1 espresso machine). It consists of a plunging-jet nozzle which introduces steam through a 2 mm hole into a confined cylindrical chamber, 10 mm diameter and 30 mm height, placed 5 mm above the milk surface. The negative pressure generated in the chamber draws ambient air through 3 holes, 1 mm diameter, located on the cylinder wall, which is dispersed along with the steam into the milk.

2.2.2. Ejector-type nozzle

It was adapted from a commercial espresso machine (Krupps Vivo): Two stainless steel tubes were connected to a rubber sparger as shown in Fig. 1B, steam was introduced through one of the tubes, and air was drawn in through the other (7 cm length) like an ejector system. A mixture of steam and air left the nozzle through a 1 mm orifice at the tip of the rubber unit. The sparging unit was placed in such a way that the orifice on the rubber unit was located 10 mm below the surface of the milk.

2.2.3. Plunging-jet nozzle

A 5 mm commercial nozzle (Fig. 1C) with 3 holes of 1 mm each was used. The nozzle tip was fixed 5 mm above the milk surface, which gave repeatable foam properties.

2.3. Foam generation methodology

A fixed volume of milk, 200 mL, was taken in a 1 L graduated cylinder (reading error of ±10 mL), and the sparging unit was placed above or below the milk surface depending on the nozzle studied. The steam was injected at a constant flow rate over a period of time which gave a maximum temperature of about 70 °C in the milk. The injection time depended of the steam pressure and nozzle type (Table 1). Temperatures were measured continuously

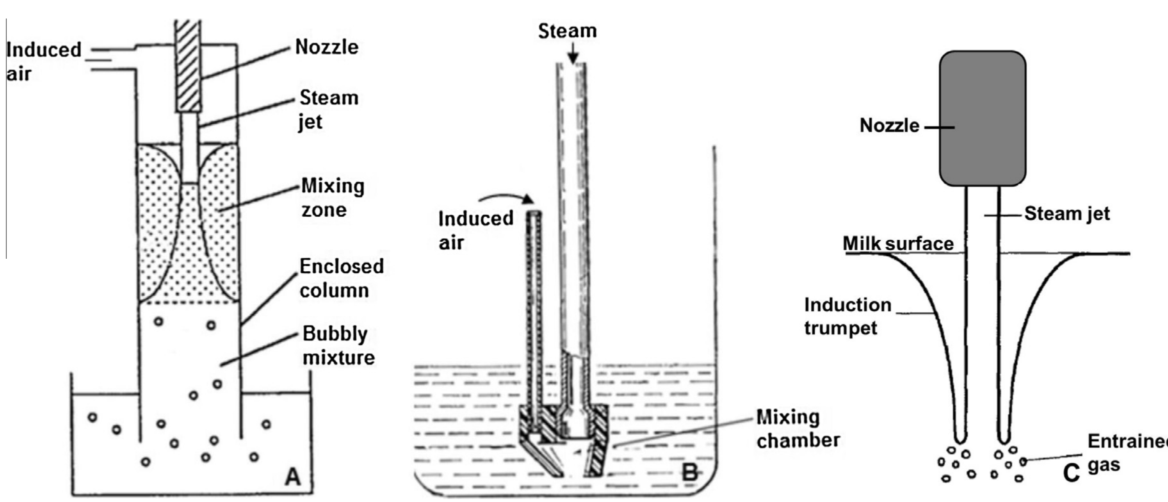

Fig. 1. Nozzles used to produce milk foams: (A) confined-jet, (B) ejector-type and (C) plunging-jet.

Table 1
Steam injection time to get a final temperature between 65 and 70 °C in milk foams produced with different combinations steam pressure – nozzle.

Steam pressure (kPa)	Type of nozzle		
	Confined-jet (s)	Ejector-type (s)	Plunging jet (s)
100	28	70	29
180	20	53	21
280	15	38	16

Table 2
Definition of parameters used to evaluate the foamability and stability in foams.

Volume of foam (V_F)	$V_F = V_T - V_L$
V_T: total volume of foam column, V_L: volume of clear liquid	
Volume of liquid held within the foam (V_{LF})	$V_{LF} = V_{LT} - V_L$
V_{LT}: volume of milk plus condensed steam	
Volume of air held within the foam (V_{AF})	$V_{AF} = V_F - V_{LF}$
Air released fraction (ARF)	$ARF = \frac{(V_{AF})^0 - V_{AF}}{(V_{AF})^0}$
Fraction of air released from the foam in relation to the amount initially incorporated in the dispersion ($t = 0$)	
Liquid drained fraction (LDF)	$LDF = \frac{(V_{LF})^0 - V_{LF}}{(V_{LF})^0}$
Fraction of liquid drained from the foam in relation to the amount initially present in the dispersion ($t = 0$)	
Air volume fraction (ϕ)	$\phi = \frac{V_{AF}}{V_F}$
Volume of gas per unit volume of foam	

with K type thermocouples connected to a data acquisition system (Grant Systems 10003 Squirrel). One of the thermocouples was placed approximately 2 cm above the anticipated interface level and the other 2 cm below the interface, in order to measure the foam and liquid temperatures, respectively.

2.4. Foam properties

2.4.1. Foamability and stability

The foam allowed to destabilize in the same graduated cylinder where it was formed. The volume of the dispersion was read continuously from the graduations on the cylinder, and the cylinder and contents were weighed before and after steam injection, in order to determine the mass of the steam condensed in the milk. Total (liquid plus foam) and clear liquid (only liquid) volumes (V_T and V_L, respectively) in the cylinder, and the liquid and foam temperatures were monitored over time as the foam was left to stand in a controlled temperature room (18 °C).

Foamability was evaluated by obtaining the air volume fraction (ϕ_0) (Table 2). Although there are different parameters used to measure the transient stability of foams (Britten and Lavoie, 1992; Buchanan, 1965; Carrera-Sanchez and Rodrıguez-Patino, 2005; Waniska and Kinsella, 1979), most of the earlier workers have characterized the stability on the basis of liquid drainage from the foam and the collapse of the foam column. Following the same vein, the stability of foams was studied by measuring over time: (i) the volume fraction of the liquid drained (LDF) and (ii) air release fraction (ARF).

The foamability and foam destabilization parameters were determined by undertaking a mass balance on the basis of the volume measurements made before and after switching off the steam supply using the equations defined by Silva et al. (2008), (Table 2). When the top of the foam was found to be uneven, an average reading of three points around the cylinder circumference was taken to represent the mean position of the foam top. The maximum variation in the readings was 10 mL.

2.4.2. Foam texture

Foam texture was assessed by performing a compression test using a texture analyzer (TA XT2i, Stable Microsystems, Surrey, UK) at fixed time of 3 min of destabilization. A 51 mm diameter cylindrical probe was used in all experiments. The probe compressed the sample by 5 mm at the test speed of 0.5 mm/s.

The equipment was fitted with a 5 kg load cell (sensitivity 0.1 g) for better texture detection in weaker samples. The maximum force was then selected as the parameter to compare the texture of different foams.

2.4.3. Bubble size distribution

An optical system with a CCD camera was adapted to measure the bubble size distribution. The system consisted of a set of TV lenses which allowed visualizing a minimum size of approximately 10 μm; these lenses were coupled to a CCD camera which captured the digital images and sent them to a computer to be stored for a further analysis.

The foam was sampled 2 min after the steam injection ceased, by using a polycarbonate spoon designed specially to take the foam directly from the cylinder without the need to transfer it to another container. The foam was left in the spoon for a minute to stabilize, prior to taking pictures of 4 different areas in the spoon.

The images were edited and processed using the software ImageJ 1.42 and Bubbles Edit 1.1 (a copy licence of BubbleSEdit was given kindly by its author Dr. Xenophon Zabulis from Institute of Computer Science, Foundation for Research and Technology, Crete, Greece).

3. Results and discussion

3.1. Nozzles characterization

3.1.1. Steam flow

There were significant effects of the steam pressure ($p = 0.001$) and the type of nozzle used ($p = 0.001$) on the flow rate of injected steam (Fig. 2).

Plunging-jet and confined-jet nozzles introduced steam between 1.8 (at 100 kPa) and 2.3 (at 280 kPa) times quicker than ejector-type. The flow rate of steam increased linearly with the pressure, but the rates of increase were different, with the lowest rate being noted for the ejector-type nozzle. The plunging-jet and the confined-jet nozzles can inject steam almost freely without any flow restriction produced by the air. On the other hand, the ejector-type nozzle has a mixing chamber where the steam is mixed with the air drawn (Varga et al., 2009), thus the presence

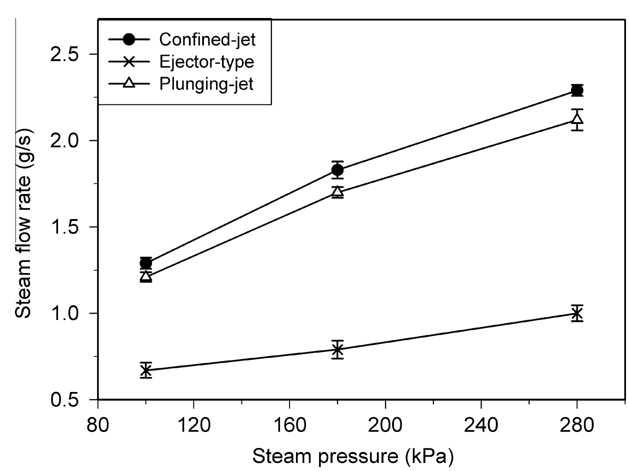

Fig. 2. Average steam flow rates injected by different nozzles at three steam pressures during generation of milk foams. Data correspond to the mean of three values and bars are the standard error.

of air in this chamber impedes the steam flow more than in other nozzles.

All foams produced were assessed after the milk was warmed between 65 and 70 °C in order to reproduce the conditions used in the preparation of the traditional barista-style milk foams in coffee shops.

3.1.2. Performance of nozzles

When milk foams are produced by steam injection, the steam is used to warm the milk as well as induce the air entry. The final temperature of milk is controlled by the injection time (at a fixed pressure), and the volume of air introduced depends on the injection time as well as the mechanism of air entry. The efficiency of any steam–air injecting nozzle can be expressed by the mean value of the ratio of the air and the steam flow rates during injection.

As the air flow depends on the flow of steam, Fig. 3 shows a direct variation of the entrainment ratio with the steam pressure for all nozzles. The rate of change was different for each nozzle: increasing the pressure, produced slight increase in the entrainment ratio for ejector-type and confined-jet nozzles which eventually tend towards constant values at higher pressures. On the other hand, the results for plunging-jet nozzle showed a significant effect of pressure on entrainment ratio with higher rates of changes at higher pressures.

This is a consequence of the mechanism of air entrance: confined-jet and ejector-type nozzles introduce air by the vacuum caused by steam expansion. As the air and steam are mixed in a closed space before their injection into milk, an increase in steam pressure generates greater pressure drop and steam hold-up inside the nozzle, which effectively reduces the entrainment ratio (Varga et al., 2009). However, the mechanism of air inclusion is different in the plunging-jet nozzle: the air is introduced as a thin layer entrained by the steam jet at its surface. As the steam pressure rises, the impact velocity of the steam jet also increases dragging more air and consequently getting higher entrainment ratios, as shown by Brattberg and Chanson (1998) and Bagatur et al. (2002).

3.2. Bubble size

Two variables were measured to study the bubble populations in foams obtained under the different conditions of pressure and nozzle type: the Sauter mean diameter (D_{32}) which is related to the bubbles size distribution and the inter-percentile range 10–90 (IPR10–90) which is a measure of the dispersion in the bubbles size (polydispersity).

The effect of pressure on D_{32} in foams produced with the three nozzles is showed in Fig. 4. There was a linear increase in bubble size with steam pressure for each nozzle, but this effect was less marked for plunging-jet nozzle, since the D_{32} increased by only 3 μm for a 20 kPa increase in pressure. In contrast, the foams produced with confined-jet and ejector-type nozzles changed bubble size by 11 and 10 μm respectively for 20 kPa increase in pressure. These inferences can be drawn from the gradient of the best fit lines drawn through the points shown in Fig. 4, for each nozzle. Further, the ejector-type nozzle produced the biggest bubbles at each steam pressure, while the plunging-jet generated the smallest bubbles.

It is interesting to note that bubble size was affected by pressure more significantly in foams produced with the confined-jet and ejector-type nozzles than with the plunging jet nozzle.

From the definition of Weber number, which relates the deformation forces acting on bubbles and the surface tension forces counteracting the bubble deformation, the maximum stable bubble diameter (Evans et al., 1992) (d_m) is given by:

$$d_m = \frac{We_c \sigma}{\rho \bar{u}^2}$$

where ρ and σ are the surface tension and liquid density, respectively; $\bar{u}^2$ is the average of the squares of the velocity differences in the vicinity of the bubbles; and We_c is the critical Weber number at which a bubble splits up, which can be taken as 1.18–1.20 for bubble breakup in a turbulent flow (Evans et al., 1992; Hinze, 1955). Thus, the maximum stable bubble diameter is inversely proportional to the level of turbulence in the system, which also depends on the fluid velocity (Evans et al., 1992). Thus, a decrease in the bubble size is expected with increase in steam pressure on the basis of the existence of We_c, but this was not observed, as evident in Fig. 4. However, it is necessary to take into account other processes which occur concurrently or after bubble formation: Varley (1995) found that bubble size declined with increasing fluid velocity only if the entrainment ratio (ER) remained constant. This was not the case in the present study (Fig. 3). Varley (1995) also suggests that if ER increased with the steam flow, the local gas phase hold up is high and the probability of bubble collision and coalescence is greater leading to the formation of larger bubbles. This effect is more pronounced in confined-jet and ejector-type nozzles compared to plunging-jet, where the mixture of steam

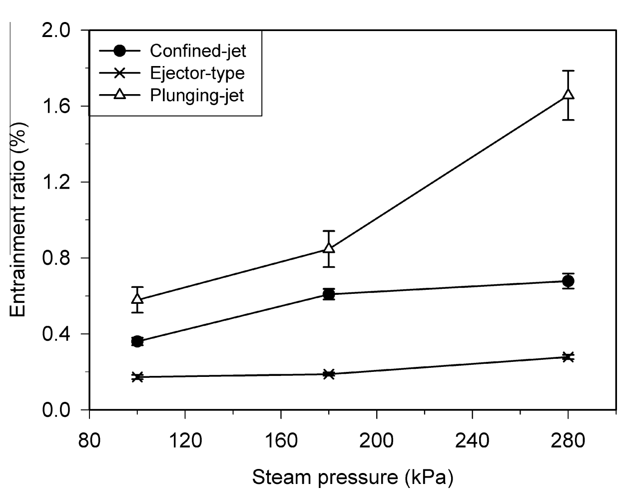

Fig. 3. Entrainment ratio (air flow/steam flow) for nozzles used to generate foams at different steam pressures. Data correspond to the mean of three values and bars are the standard error.

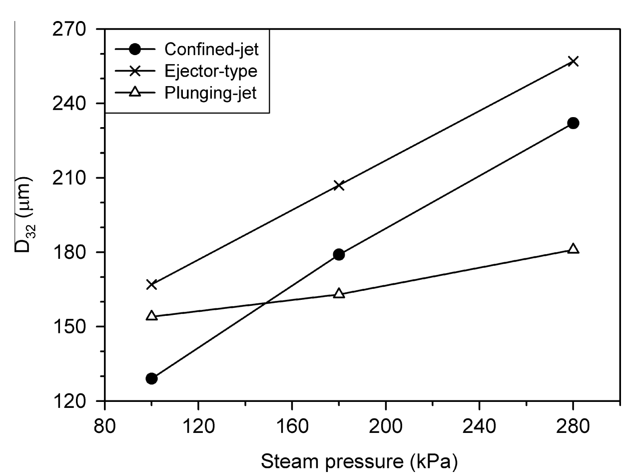

Fig. 4. Sauter mean diameter (D32) for bubbles in milk foams obtained under different steam pressure – nozzle type conditions. Values were calculated for a minimum of 1000 bubbles.

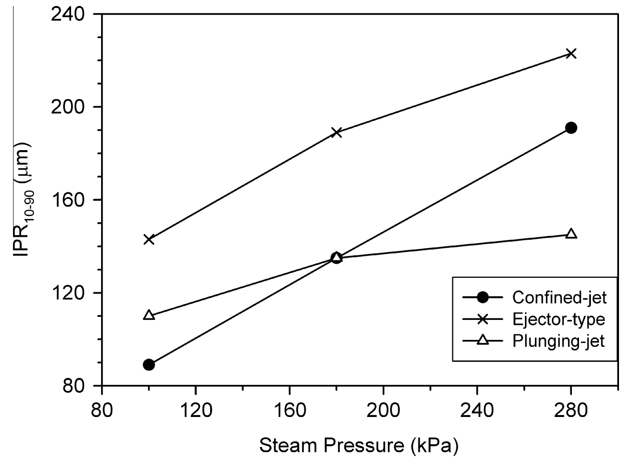

Fig. 5. Inter-percentile range 10–90 (IPR10–90) for bubbles size population in milk foams obtained under different conditions of steam pressure – nozzle type. Values were calculated for a minimum of 1000 bubbles.

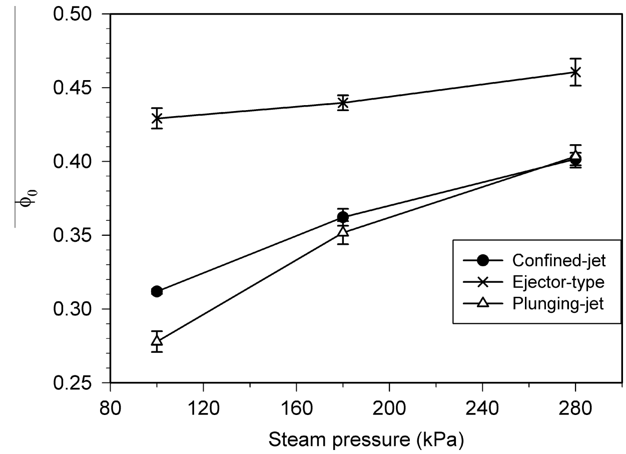

Fig. 7. Foamability measured as the initial gas volume fraction (ϕ_0) in milk foams obtained using different combinations of steam pressure and nozzle type. Values represent the mean of 3 values and the bars represent the standard error of the mean.

and air are confined in smaller spaces, and the coalescence probability is higher.

The other consequence of higher bubble coalescence with increasing ER is a higher spread in bubbles size (Varley, 1995) as shown in Fig. 5. This was more relevant in the case of confined-jet and ejector-type nozzles than for the plunging jet nozzle. These results show that the foams became more polydispersed with increasing steam pressure, and it was more marked in the case of the confined-jet and ejector-type nozzles.

Fig. 6 presents representative images of the bubbles in foams produced at 280 kPa.

The image of bubbles obtained with the plunging-jet nozzle shows smaller bubbles and more homogeneous bubble size distribution, which allows a better packing of bubbles in the foam. Further, neither deformation nor compression is observed in the bubbles. The ejector-type nozzle gave the largest bubbles which appeared deformed and slightly compressed, whereas the bubbles produced with the confined-jet nozzle were slightly smaller in size but less packed than those obtained using the ejector-type nozzle.

3.3. Foamability

Foamability is related directly to the quantity of air injected and the capacity of the proteins to retain this air once the foam is created (Marinova et al., 2009). Since the same type of milk was used in all experiments, the amount of air incorporation in the foam (Fig. 7), which is also equal to the volume of air injected, depends only on the steam pressure and nozzle type used to generate the foams.

There was a significant effect ($p < 0.001$) of the pressure and nozzle type on ϕ (Fig. 7). The direct relationship of ϕ with the increasing pressure was more evident in the case of the plunging jet nozzle. No significant changes were observed in foams generated with ejector-type nozzle. It is important to highlight that ϕ_0 was also controlled by the design and placement of the nozzles: the quantity of air introduced in the case of the confined-jet and plunging jet nozzles depends on the air entry tube length in the injector-type nozzle (7 cm in this experiment) and the initial position of the nozzle tip above the milk surface (in this case, 5 mm). This is because air entrainment ceases when the foam height increases to a level where it covers the air entry point. This consideration allows explaining the different effects of pressure change on ϕ_0 for each nozzle: as the foam height reaches the position of the air entrance tube in the ejector-type nozzle, the air flow decreases drastically regardless of the pressure, resulting in a minimum effect of pressure increase on ϕ_0. On the other hand, a high speed jet of steam hits the milk surface in the case of the confined-jet and plunging jet nozzles, creating a cavity in the liquid as consequence of the stagnation pressure (Ohl et al., 2000). As the speed of the jet increases with the steam pressure, the cavity size becomes bigger which entraps more air and results in a significant increasing of ϕ_0 with pressure.

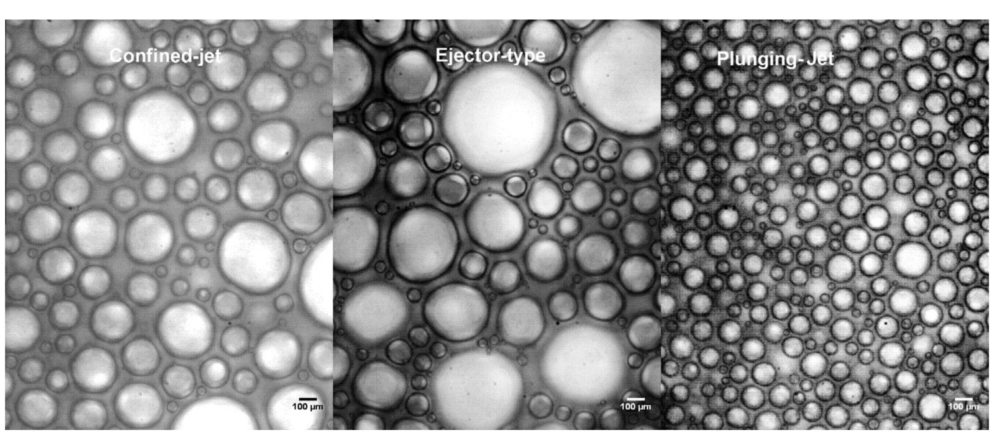

Fig. 6. Representative images of bubbles in milk foams obtained with different nozzles at 280 kPa. Images were taken 3 min into the destabilization process.

3.4. Foam stability

3.4.1. Liquid drainage

Liquid drainage was studied by calculating the liquid drained fraction (LDF) during destabilization process. Fig. 8 shows that foams produced at 100 kPa drained quickly within the first 2 min, whereas those generated at 280 kPa drained more slowly in the same interval of time. Profiles were more homogeneous after 4 min with the exception of foams produced with the ejector-type nozzle which drained slowly, shedding liquid in smaller quantities (less than 93%).

The influence of pressure was more significant in foams produced with plunging-jet nozzle in the early stages of destabilization. Thus foams made at 100 kPa drained 92% of liquid at 2 min, whereas foams produced at 280 kPa only drained nearly 80% during the same time. On the other hand, the steam pressure did not affect the profiles of liquid drainage in foams generated with ejector-type nozzle, since all foams drained about ~78% after 2 min of destabilization for different steam injection pressures.

Data on the volumes of liquid drained were fitted to the model developed by Elizalde et al. (1991) to make a quantitative comparison of destabilization and drainage in the foams (Fig. 9). There was a significant effect of the interaction ($p < 0.019$) of the steam pressure and the nozzle type used on the kinetic parameters. As the initial rate of liquid drainage (R_{0L}) relates to the ability to retain excess liquid in foams with low gas volume fraction (Britten and Lavoie, 1992), this parameter was used instead of half-life time of drainage (B_L) to compare the rates of drainage. There was a significant effect of the pressure and nozzle type on rates of liquid drainage ($p < 0.001$): it decreased with pressure for confined-jet and plunging-jet nozzles, and remained practically constant for foams produced with the ejector-type nozzle. It is interesting to note the marked effect of steam pressure on R_{0L} for foams made with plunging-jet nozzle since it decreased from 2410 to 670 mL/min when the pressure increased from 100 to 280 kPa. On the other hand, the lowest initial drainage rates were observed in foams produced using ejector-type nozzle, this is due to the low initial content of liquid in these foams.

A variety of factors are associated with the speed and the extent of liquid drainage in foams: gas flow rate during the foam production, bubble size, initial height of foam column and liquid properties (Narsimhan, 1991). As these parameters were different and not controlled in present experiments it is not possible to attribute the observed performance to any one factor, and a combined effect of these variables is expected. However, a partial explanation can be given by relating the initial rate of liquid drainage with the product of D_{32} and ϕ_0. Fig. 10 shows an inverse relationship: R_{0L} is higher for smaller products $D_{32} * \phi_0$ as observed in present study, for example the greatest R_{0L} was 2488 mL/min which was observed in foams produced with the plunging jet nozzle at 100 kPa, these had the smallest bubble size and the highest initial liquid content.

If bubbles are greater than the optimum size as stated by Germick et al. (1994), the extent and rate of liquid drainage increases as the bubbles become smaller. This is because the gradient of plateau border suction (which opposes gravity) is smaller in bigger bubbles. On the other hand, a high initial content of liquid in the foam generates more homogeneous foams; the gradient of plateau border suction is smaller and the gravity accelerates drainage.

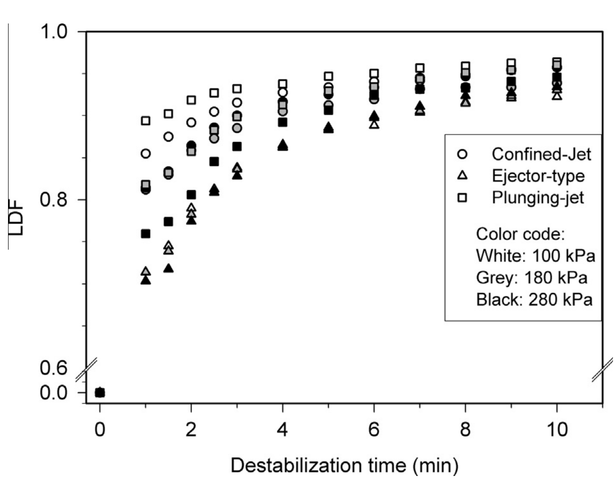

Fig. 8. Liquid drainage fraction during destabilization of milk foams obtained under different conditions steam pressure and nozzle type. Values represent the mean of 3 values and the error bars were omitted to avoid confusion.

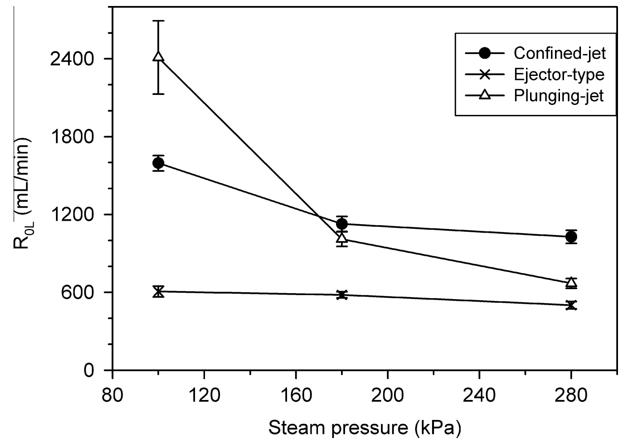

Fig. 9. Estimated values for the initial rate of drainage (R_{0L}) in milk foams obtained using different combinations of steam pressure and nozzle type. Values represent the estimated value for 3 replicates and the bars are the standard error of the estimated.

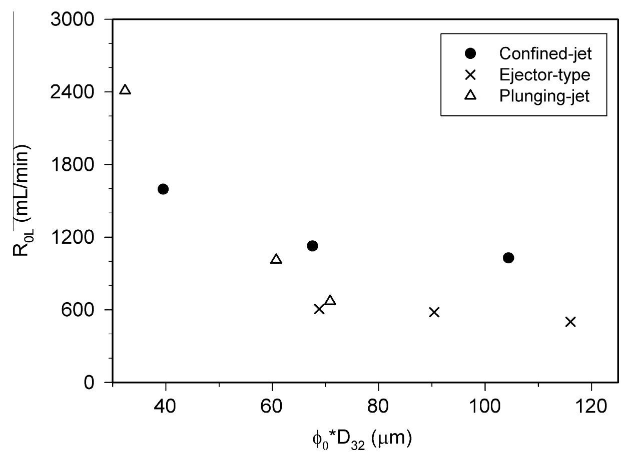

Fig. 10. Variation of the initial rate of liquid drainage (R_{0L}) with the product of gas volume fraction and Sauter diameter (D_{32}).

3.4.2. Air release

As a consequence of liquid drainage, the liquid film between bubbles becomes thinner and eventually ruptures. This phenomenon plus the disproportionation process result in foam collapse (Carrier and Colin, 2003), which is accompanied by air release. Fig. 11 shows how the air release fraction (ARF) for the different foams changes with destabilization time.

The value of this fraction after 10 min depended on the steam pressure employed and the nozzle used to create the foam.

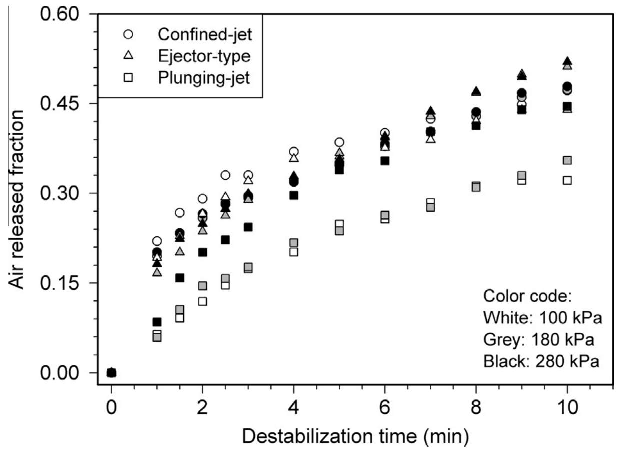

Fig. 11. Air release fraction in milk foams obtained with different combinations of steam pressure and nozzle type. Values represent the mean of 3 values and the error bars were omitted to avoid confusion.

When the ejector-type nozzle was used, ARF only increased for steam pressures between 100 kPa and 180 kPa, remaining unaltered at 280 kPa. In the case of the plunging-jet nozzle, the ARF increased for the same three pressure values. When the confined-jet nozzle was used, the ARF remained unaltered for all three steam pressure values. Fig. 11 also shows the rate of air release was higher in the case of confined-jet and ejector-type nozzles during the first 5 min, when the steam pressure employed was 100 kPa; thereafter, the profiles were similar for these two nozzles, with the ejector-type nozzle giving slightly higher values.

Even though Britten and Lavoie (1992) found three distinct zones of rates for gas release from milk protein foams, Fig. 11 only shows a roughly constant rate of foam collapse which corresponds to the second stage of the rate profiles observed by Halling (1981). These differences may be attributed to the different foaming temperatures: Britten and Lavoie (1992) worked at 20 °C, so the collapse of the foam column was slower, and all three stages were observed. On the other hand, the temperature of the present foams was 65 °C at the beginning of destabilization, so the foam collapse was rapid and the time necessary to achieve the critical lamella thickness was likely to be so short that the first stage is not noticeable. Moreover, the final stage was also not observed in this study because it generally occurred after very long times, for instance, Britten and Lavoie (1992) observed this stage after 40 min of destabilization.

3.5. Foam texture

Fig. 12 presents the compression force at a strain of 5% for foams produced with the different combinations of steam pressure and nozzle design.

There was a significant effect of steam pressure ($p < 0.001$) on compression force, which increased with the pressure in all foams, but the change was greater in foams made with plunging-jet nozzle, which also produced the strongest foams at each pressure. Although there is no information available which can explain the differences between compression force values, the differences can be related to the bubble size, extent of polydispersity and gas volume fraction. Fig. 13 shows the changes in compression force with specific interfacial area in the different foams. There is a decrease in the force with the interfacial area, which means that the foams are easier to compress when the bubble size is small and/or the holdup is high. The fact that there is a curve for each nozzle suggests there are other factors intrinsic to each steam nozzle influencing the compression forces.

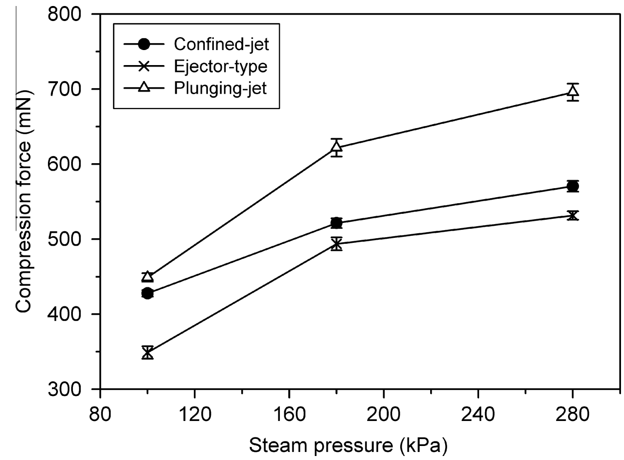

Fig. 12. Compression force and compression energy at strain of 5% for foams obtained with different combinations of steam pressure and nozzle design. Values represent the mean of 3 values and the error bars are the standard error of the mean.

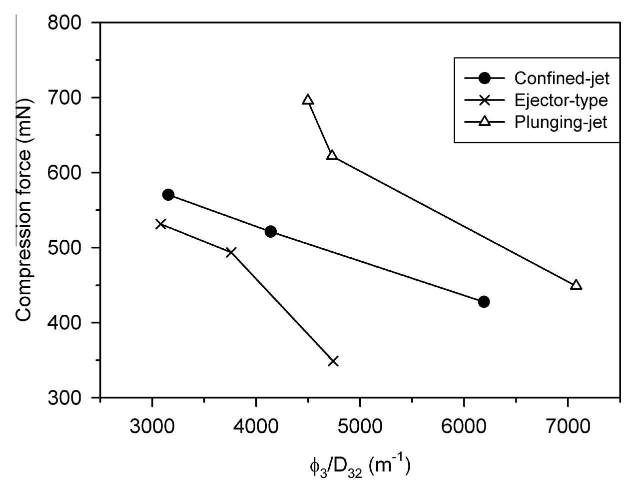

Fig. 13. Relationship between the compression force at strain of 5% and the interfacial area at 3 min of destabilization in foams obtained with different combinations of steam pressure and nozzle design.

4. Conclusions

The use of different type of nozzles and steam injection pressures produce foams with significantly different properties. The increase in steam pressure reduced the steam injection time required to produce the foams and improved foamability, stability and texture in the foams.

The mechanism of air entry determined the extent of changes in foams properties when steam pressure increased. Thus, in nozzles where the mixture of steam and air was confined (confined-jet and ejector-type nozzles), increasing steam pressure strongly influenced foam bubble size and texture, whereas the change in these properties was less marked when the air was introduced unconfined as in the case of the plunging-jet.

In general, foams produced between steam pressures of 180 and 280 kPa with the plunging-jet nozzle had desired combination of low bubble size, high foam stability and stiffness (measured as a compression force).

Finally, it was found that gas volume fraction and bubble size are related to liquid drainage and compression force, since the initial rate of liquid drainage changed inversely with the product of ϕ_0 and D_{32}, and the compression force decreased with the specific interfacial area which is proportional to ϕ_0/D_{32}.

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